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Comparison of Three-Phase Distribution Transformer Banks Against Three-Phase Distribution Transformers

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Abstract-- This paper compares the mass and the total owning cost (TOC) of three-phase distribution transformer banks against three-phase distribution transformers and the comparison is based on the minimum TOC. This is achieved through a field validated distribution transformer design program that automatically minimizes the objective function (TOC). Transformers compared in this paper are of shell-type, immersed in oil, and all are designed to meet the standard NMX-ANCE-2006-J116 in Mexico. The conclusion of this paper is that from the viewpoint of minimum mass and minimum TOC, in case of small-size transformers (smaller than 45 kVA) it is recommended to use three-phase transformer banks, which is in disagreement with transformer textbooks. This result is due to the fact that more mass is needed for transformer tank, oil and high-voltage conductor for three-phase transformer in comparison to three-phase transformer bank.

***Index Terms*-- Cost of transformer materials, total owning cost, transformer mass, distribution transformers, single-phase distribution transformers, three-phase distribution transformers.**

I. INTRODUCTION

THE transformer is an essential component in the electrical power system. A typical transformer consists of coils of wire conductor insulated with paper insulation, which are assembled to the core. The transformer is filled with dielectric oil, which serves as insulation and as a heat transfer medium.

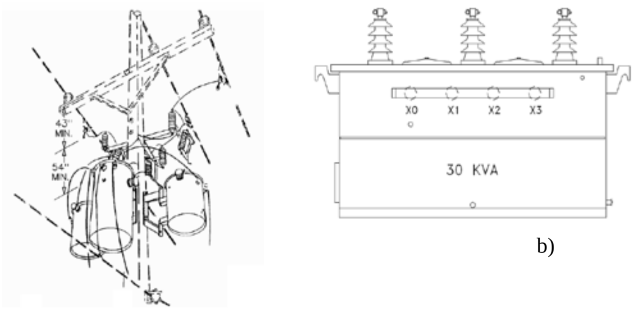
Hungarian engineers Deri, Blathy and Zipernowsky in 1885 created the first single-phase transformer that consisted of an iron toroid with two windings [1]-[2]. This transformer had a size of 1.4 kVA at 40 Hz and a voltage ratio 120/72 V. Russian engineer Mikhail Dolivo-Dobrovolsky built the three-phase transformer five years after the manufacturing of the first single-phase transformer [1]. There are three main reasons why three phases are used in electrical power systems, a) a three-phase machine can generate up to 95.5% of an ideal machine with infinite number of phases [3], b) the use of three conductors in a three-phase system can provide 173% more power than using two conductors in a single-phase system [5], and c) three-phase power can be transmitted over long distances with small wire gauges.

Three single-phase transformers can be connected to form a three-phase transformer bank. For transformers, as a particular case, there are three advantages of using a three-phase transformer instead a of three-phase transformer bank [5]-[10]: a) cost reduction, b) mass reduction, and c) reduced space.

The paper is related with distribution transformers. When a transformer is used for distribution service (the secondary is connected directly to the customer load), it is called a distribution transformer. Distribution transformers are distinguished from power transformer, which are employed in high-voltage transmission systems for the transmission of large amount of power.

Power is generated, transmitted, and distributed by means of three-phase transmission lines. This requires the use of three-phase transformers to transform the voltages from one level to another. There are two options: A three-phase transformer bank or a three-phase transformer. A three-phase transformer bank is two or three single-phase transformers connected as a three-phase transformer. A three-phase transformer has three primary winding and three secondary windings mounted on a core and the windings are connected internally. These two possible options of transformers are shown in Figure 1. There are four standard ways of connecting a three-transformer bank: Y-Y, Δ-Δ, Δ-Y and Y-Δ. A three-phase transformer bank has the advantage that each unit in the bank could be replaced individually in case of failure; for example, the open delta (V-V) and the open-Y-open-delta connections are generally employed in case of emergency to guarantee continued service. These are two ways to perform three-phase transformation with only two transformers. Figure 2 shows the proper connections for three-phase distribution transformers connected to a three-phase wye primary voltage system to obtain 208Y/120 volts.

Furthermore, one spare single-phase transformer is usually all that is required to assure sufficient reliability for the entire bank. With a three-phase transformer, an additional spare three-phase transformer would be required, so the total cost of the installation plus a spare transformer is twice the cost of the installation alone. The total cost of a bank of single-phase transformers plus a spare is only 133% the cost of the bank alone. Therefore, the total cost of a bank of single-phase transformers plus a spare is probably less than the cost of a three-phase transformer plus a spare. For instance, it may be impossible or impractical to fabricate or ship a three-phase power transformer with an extremely large kVA capacity. A bank of three single-phase transformers may then be the solution.



a)

b)

Figure 1. Transformer for three-phase circuits can be constructed in two ways: a) three-phase transformer bank on a pole, b) three-phase transformer.

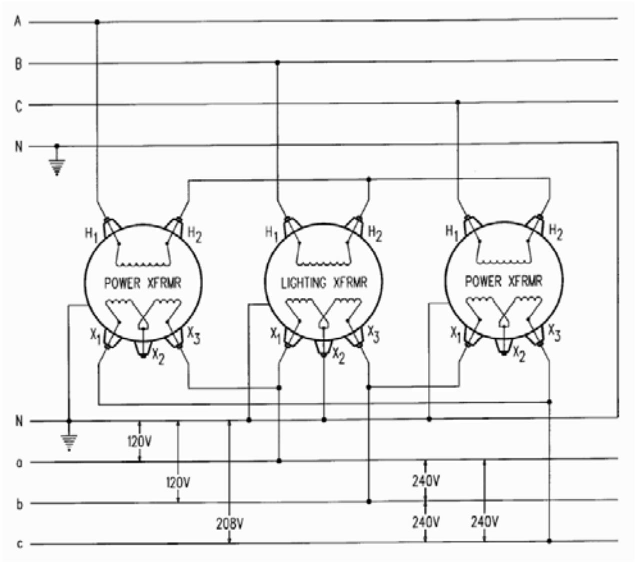


Figure 2. Three single-phase distribution transformers connected.

a)

b)

Figure 3. a) Shell-type single-phase transformer, b) Shell-type three-phase transformer.

The shell-type three-phase transformer includes the five-legged core form design. In the five-legged core form design, three sets of windings are placed over three central vertical core legs. The shell-type single-phase transformer includes the three-legged core form design. In the three-legged core form design, one set of windings is placed over the central vertical core legs. A shell-type single-phase transformer and a shell-type three-phase transformer are shown in Figure 3.

This paper arises because of the interest to further investigate three-phase distribution transformers against three-phase distribution transformer banks taking into account the current cost of transformer materials and the labor cost to manufacture the transformer. This is particularly important taking into account that some of transformer materials are stock exchange commodities with fluctuating prices on a daily or weekly basis. The comparison of three-phase distribution transformer banks against three-phase distribution transformers is done by using a field validated transformer design program, for single-phase and three-phase transformers, minimizing the transformer TOC while meeting all the restrictions that are imposed by the standard NMX-ANCE-2006-J116 in Mexico [11].

II. COMPARISON METHODOLOGY

This section briefly presents the methodology and the computer program for the optimal design of single-phase and three-phase distribution transformers that was developed for the study and comparison of three-phase transformer banks and three-phase transformers.

2.1 Input data

The transformer design program requires the following data:

a) Transformer size (kVA).
b) Number of phases.
c) Connection type.
d) High voltage (V).
e) Low voltage (V).
f) Frequency (Hz).

2.2 Variables

The optimization routine (see Section 2.5), considers five design variables. These variables and its ranges are:

a) High voltage conductors from 6 to 27 AWG.
b) Magnetic flux density from 1.4 to 1.7 T.
c) Number of turns of low voltage. The variation of this parameter is from 5 to 50, in case of single-phase transformers, while the expression $N_{LV} = 89.6828 \cdot kVA^{-0.5}$ reduces the search range, where N_{LV} is the number of turns of low voltage and kVA is the transformer size.
d) Width of core steel sheet. There are 6 widths between 152.4 mm and 304.8 mm.
e) Cross-section area of aluminum foil for low voltage. There are 7 values available. The width of aluminum foil varies from 114.3 mm to 254.0 mm. The thickness of aluminum foil varies from 0.30 mm to 1.78 mm.

2.3 Transformer design program

The transformer design program make the computation of the following three fundamental parameters:

a) Transformer mass.
b) Transformer material cost.
c) Transformer total owning cost (TOC).

2.3.1 Transformer mass

The transformer mass is function of the equipment design, and include the core, high-voltage conductor, low-voltage conductor, tank and oil. The core mass for three-phase transformers is given by:

$$M_c = 2 \cdot (P_{t1} + P_{t2}), \qquad (1)$$

where P_{t1} is the lateral core mass (kg) and P_{t2} is the central core mass (kg).

The core mass for single-phase transformers is given by:

$$M_c = 2 \cdot P_{t1}. \tag{2}$$

Reader interested in the calculation of P_{t1} and P_{t2} can consult [12], [13].

The high-voltage conductor mass, M_{HV}, is derived from:

$$M_{HV} = MT_{HV} \cdot N_{HV} \cdot F \cdot cs_{HV} \cdot \rho_{HV} \tag{3}$$

where MT_{HV} is the mean length of high-voltage turn (m), N_{HV} is the number of turns of high-voltage conductor, F is the number of phases, cs_{HV} is the cross-section area of high-voltage conductor (m^2), and ρ_{HV} is the mass density of high-voltage conductor (kg/m^3).

The low-voltage conductor mass, M_{LV}, is derived from:

$$M_{LV} = MT_{LV} \cdot N_{LV} \cdot F \cdot cs_{LV} \cdot \rho_{LV} \tag{4}$$

where MT_{LV} is the mean length of low-voltage turn (m), N_{LV} is the number of turns of low-voltage conductor, F is the number of phases, cs_{LV} is the cross-section area of low-voltage conductor (m^2), and ρ_{LV} is the mass density of low-voltage conductor (kg/m^3).

The tank mass, M_{ta}, is derived from:

$$M_{ta} = (V_{ct} + V_{ft} + V_{tt}) \cdot \rho_{ac} \tag{5}$$

where V_{ct} is the volume of carbon steel plate of tank body (m^3), V_{ft} is the volume of carbon steel plate of tank bottom, V_{tt} is the volume of carbon steel plate of tank cover, and ρ_{ac} is the mass density of steel (kg/m^3).

The transformer total mass, M_t, is calculated from [14]:

$$M_t = M_{HV} + M_{LV} + M_c + M_{ta} + M_{oil} \tag{6}$$

where M_{HV} is high-voltage conductor mass (kg), M_{LV} is low-voltage conductor mass, M_c is core mass, M_{ta} is tank mass, and M_{oil} is mineral oil mass.

2.3.2 Transformer material cost

The transformer material cost is given by:

$$C_{mat} = uc_{HV} \cdot M_{HV} + uc_{LV} \cdot M_{LV} + uc_c \cdot M_c + uc_{ta} \cdot M_{ta} + uc_{oil} \cdot M_{oil} \tag{7}$$

where uc_{HV} is the unit cost of high-voltage conductor (\$/kg), M_{HV} is high-voltage conductor mass (kg), uc_{LV} is the unit cost of low-voltage conductor (\$/kg), M_{LV} is low-voltage conductor mass (kg), uc_c is the unit cost of core magnetic material (\$/kg), M_c is core mass (kg), uc_{ta} is the unit cost of tank steel (\$/kg), M_{ta} is tank mass (kg), uc_{oil} is the unit cost of mineral oil (\$/kg), and M_{oil} is mineral oil mass (kg).

2.3.3 Transformer total owning cost

The total owning cost takes into account not only the initial transformer cost but also the cost to operate and maintain the transformer over its life. The *TOC* is given by:

$$TOC = BP + A \cdot NLL + B \cdot LL, \tag{8}$$

where:

$$BP = \frac{C_{mat} + C_{lab}}{1 - SM}, \tag{9}$$

where BP is transformer bid price (\$), A is transformer no-load loss cost rate (\$/W), NLL is transformer no-load loss (W), B is transformer load loss cost rate (\$/W), LL is transformer load loss (\$), C_{mat} is transformer material cost (\$) that is computed using Equation (7), C_{lab} is transformer labor cost (\$), and SM is transformer sales margin. Methods for computing A and B loss cost rates can be found in [12], [15].

2.4 Constraints

The optimization process considers a group of constraints related with the excitation current, no-load losses, total losses, impedance and efficiency. Table 1 shows the no-load and total loss constraints for distribution transformers. The minimum efficiencies versus the transformer rating and insulation class for single-phase transformers and three-phase transformers can be seen in Table 2, which has been taken from the Mexican standard [11]. According to [11], the excitation current should not exceed 1.5% in all single-phase transformers as well as for three-phase transformers with capacity greater than 45 kVA. In case of three-phase transformers up to 45 kVA, the excitation current should not be larger than 2.0%. Table 3 shows the impedance constraints for single-phase and three-phase distribution transformers. The impedance depends on the insulation class and the transformer rating.

Table 1. Maximum no-load losses (W) and maximum total losses (W) required by the Mexican standard [11] for single-phase and three-phase transformers.

Size (kVA)		Basic Impulse Insulation Level, BIL (kV)					
		BIL≤95		**95<BIL≤150**		**150<BIL≤200**	
		No-load	Total	No-load	Total	No-load	Total
Singles-phase transformers	5	30	107	38	112	63	118
	10	47	178	57	188	83	199
	15	62	244	75	259	115	275
	25	86	368	100	394	145	419
	37.5	114	513	130	552	185	590
	50	138	633	160	684	210	736
	75	186	834	215	911	270	988
	100	235	1061	265	1163	320	1266
	167	365	1687	415	1857	425	2028
Three-phase transformers	15	88	314	110	330	135	345
	30	137	534	165	565	210	597
	45	180	755	215	802	265	848
	75	255	1142	305	1220	365	1297
	112.5	350	1597	405	1713	450	1829
	150	450	1976	500	2130	525	2284
	225	750	2844	820	3080	900	3310
	300	910	3644	1000	3951	1100	4260
	500	1330	5561	1475	6073	1540	6588

2.5 Multiple design optimization algorithm

The transformer design optimization problem is solved using a multiple design method that assigns many alternative values to the design variables so as to generate a large number of alternative designs and finally to select the design that satisfies all the problem constraints with the optimum value of the objective function [12], [16].

Table 2. Minimum efficiencies (%) required by the Mexican standard [11] for single-phase and three-phase transformers.

	Size (kVA)	Basic Impulse Insulation Level, BIL (kV)		
		BIL**≤95**	**95<BIL≤150**	**150<BIL≤200**
Single-phase transformers	5	97.9	97.8	97.7
	10	98.25	98.15	98.05
	15	98.4	98.3	98.2
	25	98.55	98.45	98.35
	37.5	98.65	98.55	98.45
	50	98.75	98.65	98.55
	75	98.9	98.8	98.7
	100	98.95	98.85	98.75
	167 to 500	99	98.9	98.8
Three –phase transformers	15	97.95	97.85	97.75
	30	98.25	98.15	98.05
	45	98.35	98.25	98.15
	75	98.5	98.4	98.3
	112.5	98.6	98.5	98.4
	150	98.7	98.6	98.5
	225	98.75	98.65	98.55
	300	98.8	98.7	98.6
	500	98.9	98.8	98.7

Table 3. Impedance constraints required by the Mexican standard [11] for single-phase and three-phase transformers.

Insulation class (kV)	Impedance (%)		
	Single-phase		Three-phase
	5 kVA to 167 kVA	Pole type 15 kVA to 150 kVA	Substation type 225 kVA to 500 kVA
1.2 to 25	1.5 to 3.00	2.00 to 3.00	2.50 to 5.00
25	1.50 to 3.25	2.00 to 3.25	2.75 to 5.50
34.5	1.50 to 3.50	2.00 to 3.50	3.00 to 5.75

The five design variables and their range of variation have been presented in Section 2.2. With the range of variation of design variables (see Section 2.2), the computer program investigates a lot of candidate solutions. For each one of the candidate solutions, it is checked if all the specifications (constraints) are satisfied, and if they are satisfied, the value of the objective function is calculated and the solution is characterized as acceptable. On the other hand, the candidate solutions that violate the specification are characterized as non-acceptable solutions. Finally, among the acceptable solutions, the transformer with the optimum value of the objective function is selected, which is the optimum transformer.

III. RESULTS AND DISCUSSION

In the context of this research twelve optimal designs were created: six single-phase transformers and six three-phase transformers. M3 lamination was used for the magnetic material of all transformers.

Figures 4 and 5 show comparative graphs of transformer manufacturer TEMCo, showing that at low size, three-phase transformer banks are less expensive and they have less mass than the three-phase transformers [17]. These results were our main motivation to carry out the research of this paper.

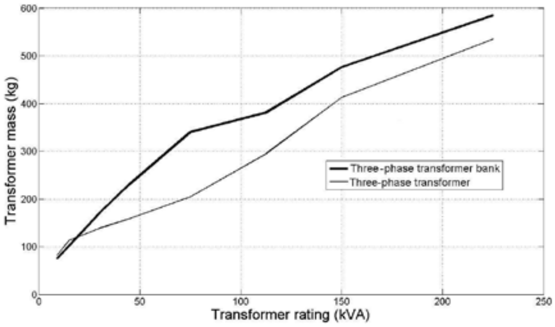


Figure 4. Mass comparison between three-phase transformers and three-phase transformer banks (transformer manufacturer TEMCo).

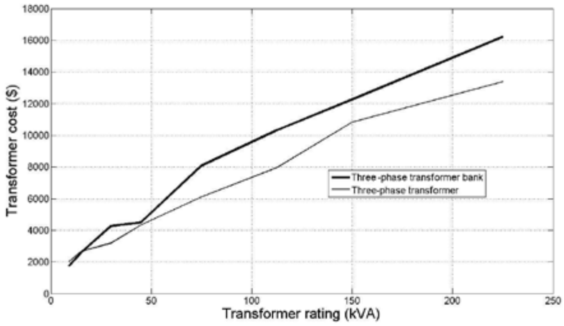


Figure 5. Cost comparison between three-phase transformers and three-phase transformer banks (transformer manufacturer TEMCo).

Figures 6 to 9 were generated using a field validated transformer design program. Figure 6 shows the trend of three-phase transformers to have less mass than three-phase transformer banks, but in low-size transformers the opposite is observed, which can be seen in more detail in Figure 7. Figure 8 shows the comparison of TOC between three-phase transformer banks and three-phase transformers. There is a trend of higher cost for three-phase transformers, however the difference in cost of low-size transformers is significantly reduced. The cost of materials for a three-phase transformer is always lower than a three-phase transformer bank, although at lower size tend to be equal, as can be seen in Figure 9. The main cause of this behavior is due to the higher mass of transform tank, oil and high-voltage conductor of three-phase transformer over three-phase transformer banks, as can be seen in Figure 10. In Figure 11 we can see the corresponding cost of each transformer component.

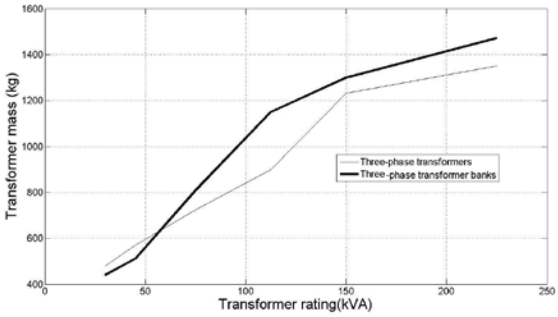


Figure 6. Total mass comparison for three-phase transformers and three-phase transformer banks.

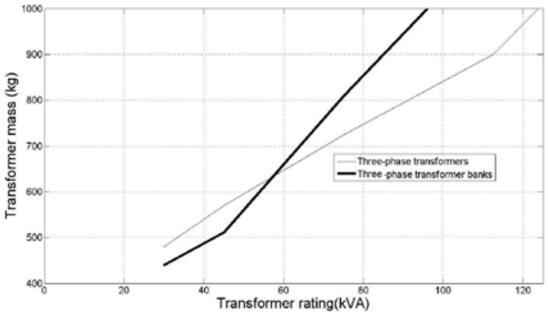


Figure 7. Zoom of Figure 6 for low-size transformers

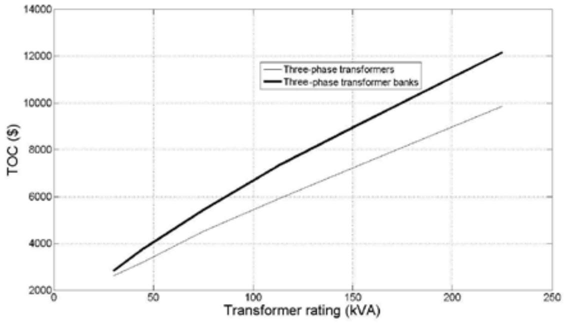


Figure 8. Total owning cost comparison between three-phase transformers and three-phase transformer banks.

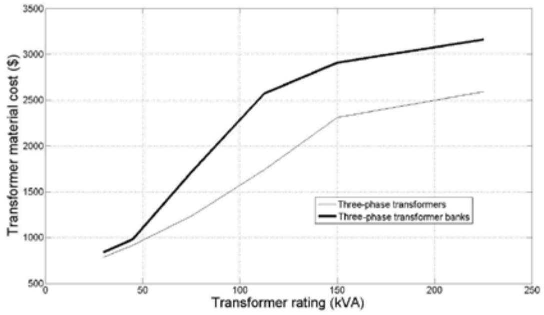


Figure 9. Material cost comparison between three-phase transformers and three-phase transformer banks.

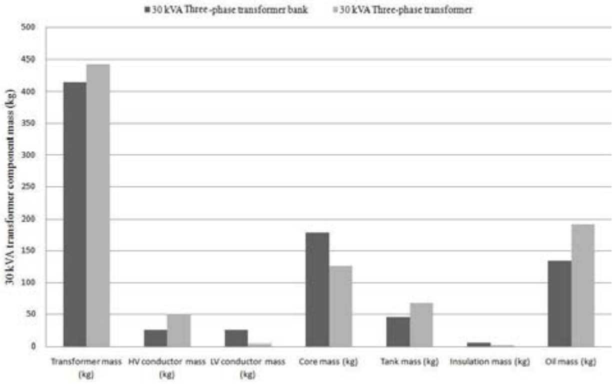


Figure 10. Mass comparison between 30 kVA three-phase transformer bank and 30 kVA three-phase transformer.

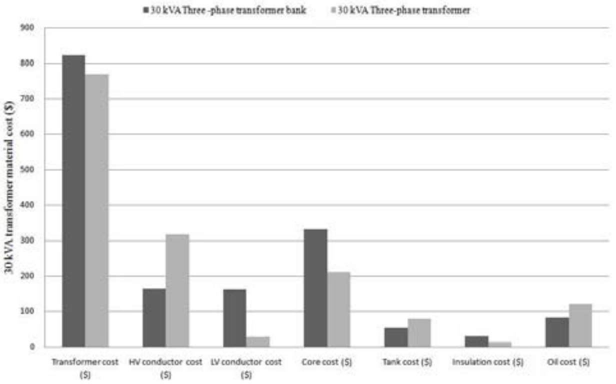


Figure 11. Transformer material cost comparison between 30 kVA three-phase transformer bank and 30 kVA three-phase transformer.

IV. CONCLUSIONS

In this paper we studied and compared three-phase transformer banks and three-phase transformers built with M3 lamination. The comparison was based on transformer TOC. We have compared a wide range of transformers with different power ratings, from 30 kVA to 225 kVA. Optimum single-phase and three-phase transformer designs were obtained using a field-validated transformer design optimization computer program that has been used for many years in a mid-size transformer factory. Specifically, twelve optimum three-phase transformer designs were created for the comparison of three-phase transformer banks against the three-phase transformers. Based on this study, we conclude that the advantage of using three-phase transformers with power rating higher than 45 kVA is strong in terms of cost and mass. However, low-size three-phase transformers have more mass, and their cost tends to be equal or great to the cost of three-phase transformer banks. The main cause of this behavior is due to the higher mass of transformer tank, oil and high-voltage conductor of three-phase transformer over three-phase transformer banks.

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VI. BIOGRAPHIES

J. C. Olivares-Galvan was born in Michoacán, México, in 1969. He received the B.Sc. and the M.Sc. degrees in Electrical Engineering from Instituto Tecnológico de Morelia (Mexico), in 1993 and 1997, respectively. He received the Ph.D. degree in electrical engineering at CINVESTAV, Guadalajara, Mexico in 2003. He is currently Professor at the Departamento de Energía of Universidad Autónoma Metropolitana (UAM). He was with Electromanufacturas S.A. de C.V., where he was transformer design engineer for eight years. He was a Visiting Scholar at Virginia Tech, Blacksburg, in 2001. His main interests are related to the experimental and numerical analysis of transformers.

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Ernesto Vázquez-Martínez received the B.Sc. degree in electronic and communications engineering and M.Sc. degree from the Universidad Autónoma de Nuevo León, Monterrey, México in 1989 and 1991 respectively. Since 1992 Dr. Vázquez has been a professor in the Mechanical and Electrical Engineering Faculty at Universidad Autónoma de Nuevo León, Monterrey, México, and from 1996, he is currently a Professor of the Ph.D. Program on Electrical Engineering in the same university. In 2000 he did a research stay in University of Manitoba, Canada, where he was working in traveling wave protection algorithms. He participated in the development of a filter sine-cosine for electrical measurement equipment built by a Mexican company and he has a patent about an adaptive digital overcurrent relay. He has lectured in 73 postgraduate and training courses in México, Venezuela and Perú, mainly oriented to power utility engineers in protective relay theory and its operation. His main research interests are in power system protection and application of artificial intelligence techniques in power systems.

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